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Chromium Recycling in the United States in 1998

By John F. Papp

U.S. GEOLOGICAL SURVEY CIRCULAR 1196–C

FLOW STUDIES FOR RECYCLING METAL COMMODITIES IN THE UNITED STATES

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FOREWORD

As world population increases and the world economy expands, so does the demand for natural resources. An accurate assessment of the Nation's mineral resources must include not only the resources available in the ground but also those that become available through recycling. Supplying this information to decisionmakers is an essential part of the USGS commitment to providing the science that society needs to meet natural resource and environmental challenges.

The U.S. Geological Survey is authorized by Congress to collect, analyze, and disseminate data on the domestic and international supply of and demand for minerals essential to the U.S. economy and national security. This information on mineral occurrence, production, use, and recycling helps policymakers manage resources wisely.

USGS Circular 1196, "Flow Studies for Recycling Metal Commodities in the United States," presents the results of flow studies for recycling 26 metal commodities, from aluminum to zinc. These metals are a key component of the U.S. economy. Overall, recycling accounts for more than half of the U.S. metal supply by weight and roughly 40 percent by value.

Charles G. Groat
Director

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FIGURES

TABLE

CONVERSION FACTORS

Multiply	By	To obtain
metric ton (t, 1,000 kg)	1.102	short ton (2,000 pounds)
million metric tons (Mt)	1,102,000	short ton

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ABSTRACT

The purpose of this report is to illustrate the extent to which chromium was recycled in the United States in 1998 and to identify chromium-recycling trends. The major use of chromium was in the metallurgical industry to make stainless steel; substantially less chromium was used in the refractory and chemical industries. In this study, the only chromium recycling reported was that which was a part of stainless steel scrap reuse. In 1998, 20 percent of the U.S. apparent consumption of chromium was secondary (from recycling); the remaining 80 percent was based on net chromium commodity imports and stock adjustments. Chromite ore was not mined in the United States in 1998.

In 1998, 75,300 metric tons (t) of chromium contained in old scrap was consumed in the United States; it was valued at $66.4 million. Old scrap generated contained 132,000 t of chromium. The old scrap recycling efficiency was 87 percent, and the recycling rate was 20 percent. About 18,000 t of chromium in old scrap was unrecovered. New scrap consumed contained 28,600 t of chromium, which yielded a new-to-old-scrap ratio of 28:72. U.S. chromium-bearing stainless steel scrap net exports were valued at $154 million and were estimated to have contained 41,000 t of chromium.

INTRODUCTION

The chemical element chromium was discovered in 1797 by Nicolas-Louis Vauquelin, a professor of chemistry at the Paris École des Mines, which was one of the new European technical universities established to bring science education to the mining industry (Weeks and Leichester, 1968, p. 271–283). The mineral chromite, which consists primarily of chromium, aluminum, iron, magnesium, and oxygen, is a source of chromium. Chromite was first exploited for the production of pigments (Gray, 1988) and the manufacture of refractory materials.

In the United States in 1998, the major use of chromium was in the metallurgical industry to make stainless steel; substantially less chromium was used in the refractory and chemical industries. The major chromium commodities are chromite ore, ferrochromium, and chromium chemicals, metal, and refractories. The major traded chromium commodity in the United States in 1998 was ferrochromium, which replaced chromite ore in 1983. Ferrochromium includes high-, medium-, and low-carbon ferrochromium; charge chrome is a type of high-carbon ferrochromium. Ferrochromium and ferrochromium silicon are chromium ferroalloys.

More than half of the chromium consumed in the United States in 1998 was used in stainless steel; all grades of stainless steel contain appreciable amounts of chromium. To be used in stainless steel, chromite ore is first smelted into ferrochromium. Most ore is smelted near the chromite ore mine, but some is shipped to smelters near inexpensive electrical power sources or near stainless steel producers. Ferrochromium is mixed with iron to make stainless steel.

The purpose of this report is to illustrate the extent to which chromium was recycled in the United States in 1998 (fig. 1, table 1) and to identify chromium-recycling trends. Most recycled chromium was part of stainless steel scrap, and smaller amounts were in superalloys. In this study, the only chromium recycling reported was that which was a part of stainless steel scrap reuse.

For the purpose of computing chromium supply from trade, the traded chromium commodities include chromite ore, chromium ferroalloys and metal, and selected chromium chemicals and pigments. On the basis of trade statistics and stainless steel scrap receipts reported by U.S. stainless steel producers, 20 percent of the 1998 chromium apparent consumption was secondary (from recycling of stainless steel scrap); the remaining 80 percent was based on net chromium commodity imports and stock adjustments. Chromite ore was not mined in the United States in 1998 (Papp, 1999).

On the basis of a different chromium material flow model, Gabler (1994, p. 18) estimated that in 1989, about 33 percent of chromium material potentially available for recycling was recycled and that the recycled material accounted for 23 percent of 1989 apparent consumption. Although the models differed for this study and Gabler's, the percentages of apparent chromium consumption from recycling were similar for 1989 (23 percent) and 1998 (20 percent).

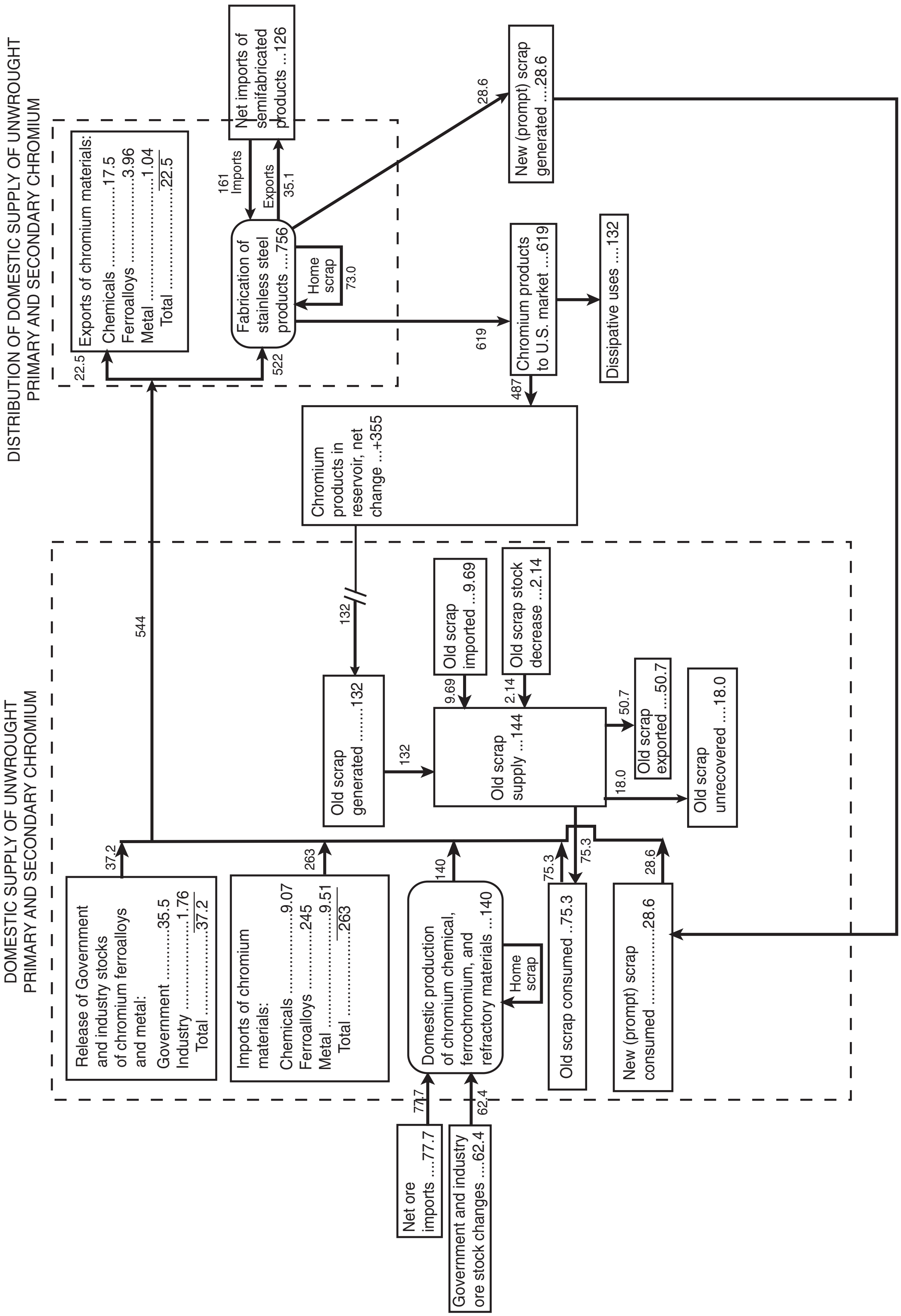

Figure 1. U.S. chromium materials flow in 1998. Values are in thousands of metric tons of contained chromium and have been rounded to three significant figures. In this study, the only chromium recycling reported was that which was a part of stainless steel scrap reuse.

Table 1. Salient statistics for U.S. chromium scrap in 1998.
[Values in thousands of metric tons of contained chromium, unless otherwise specified]

Old scrap:	
Generated[1]	132
Consumed[2]	75.3
Value of old scrap consumed[3]	$66.4 million
Recycling efficiency[4]	87 percent
Supply[5]	144
Unrecovered[6]	18.0
New scrap consumed[7]	28.6
New-to-old-scrap ratio[8]	28:72
Recycling rate[9]	20 percent
U.S. net exports of scrap[10]	41.0
Value of U.S. net exports of scrap[11]	$154 million

[1]Old scrap generated in 1998 is estimated to have been the chromium content of a fraction of the net stainless steel supply in 1968, as discussed in the text section "Old Scrap Generated." The chromium fraction of stainless steel is estimated at 0.170 (Papp, 1991, p. 20). The fraction of the 1968 supply reporting to old scrap in 1998 was 0.894. The net stainless steel supply was shipments plus imports minus exports of stainless steel mill products.

[2]Old scrap consumed is estimated to have been the chromium contained in stainless steel scrap receipts reported by consumers in 1998 less the sum of new scrap generated and scrap imports.

[3]Value is estimated to have been the annual average unit value of high-carbon ferrochromium in 1998 ($882/t of chromium or $497/t gross weight of high-carbon ferrochromium) applied to old scrap consumed. This value is used because stainless steel scrap and ferrochromium compete as sources of chromium for the production of stainless steel (Papp, 2000).

[4]Recycling efficiency is (old scrap consumed plus old scrap exported) divided by (old scrap generated plus old scrap imported plus any old scrap stock decrease or minus any old scrap stock increase).

[5]Old scrap supply is old scrap generated plus old scrap imported plus old scrap stock decrease.

[6]Old scrap unrecovered is old scrap supply minus old scrap consumed minus old scrap exported minus old scrap stock increase.

[7]New scrap (also called prompt industrial scrap) consumption is not reported. It is estimated to be the new scrap generated. See text for estimation procedure.

[8]New-to-old-scrap ratio is new scrap consumption compared with old scrap consumption, measured in weight and expressed in percentage of new plus old scrap consumption.

[9]Recycling rate is old plus new scrap consumed divided by apparent supply expressed as a percentage. Chromium apparent supply is primary domestic chromium production (from mining, which was nil for the United States in 1998) plus secondary domestic chromium production (from old plus new stainless steel scrap) plus imports minus exports plus adjustments for Government and industry stock changes. Old plus new scrap consumed is estimated to be the chromium contained in stainless steel scrap receipts reported by Fenton (2000) and updated by Duane Johnson (U.S. Geological Survey, 2000, unpub data). Chromium apparent supply used here is the same as that reported in the U.S. Geological Survey Mineral Commodity Summaries, where it is called apparent consumption (Papp, 1999).

[10]U.S. net exports of scrap are chromium contained in exports minus chromium contained in imports of stainless steel scrap.

[11]Value of U.S. net exports of scrap is the value of stainless steel scrap exports minus imports as reported by the U.S. Census Bureau on the basis of data collected by the U.S. Customs Service. Stainless steel scrap has value for reasons other than its chromium content.

In 1998, 75,300 metric tons (t) of chromium contained in old scrap was recycled in the United States; it was valued at $66.4 million. Old scrap generated contained 132,000 t of chromium. The old scrap recycling efficiency was 87 percent, and the recycling rate was 20 percent. (See appendix for definitions.) About 18,000 t of chromium in old scrap was unrecovered. New scrap consumed contained 28,600 t of chromium, which yielded a new-to-old-scrap ratio of 28:72. The U.S. Census Bureau reported that U.S. chromium-bearing stainless steel scrap net exports were valued at $154 million in 1998 and were estimated to have contained 41,000 t of chromium. Trade data reported by the U.S. Census Bureau are based on data collected by the U.S. Customs Service.

SOURCES OF CHROMIUM-CONTAINING SCRAP

Figure 1 shows secondary chromium material supply, distribution, and recycling in the U.S. economy in 1998. Stainless steel scrap was the major source of recycled chromium and is the only type of scrap reported in figure 1. In the United States, the average primary chromium supply distribution and usage trend in the metallurgical industry from 1983 through 1992, as measured by reported consumption, was stainless steel, 79 percent and increasing; alloy steel, 8 percent and decreasing; superalloys, 3 percent and increasing; and other uses, 10 percent (Papp, 1994, p. 68–70).

Steel production classifications include alloy steel (except stainless), carbon steel, and stainless steel. U.S. steel production by these classes is, in descending order of magnitude of production as a percentage of total averaged from 1993 through 1998, carbon steel, 88.8 percent; alloy steel, 9.17 percent; and stainless steel, 2.06 percent. In 1998, U.S. carbon steel production was 88.0 million metric tons (Mt); alloy steel, 8.60 Mt; and stainless steel, 2.01 Mt. Relative to steel production, stainless steel production is small.

In a world context, the United States accounted for 12.6 percent of world steel production and 15.2 percent of world stainless steel production on the basis of data from 1994 through 1998 (American Iron and Steel Institute, 1999; INCO Limited, 1999, p. 3). In 1998, U.S. stainless steel producers reported stainless steel scrap consumption of 1.04 Mt (Fenton, 2000, and updates by Duane Johnson, U.S. Geological Survey, 2000, unpub. data), or 51.8 percent of that year's stainless steel production. Consumption consisted of receipts of new, old, and home scrap. The chromium fraction of stainless steel is estimated at 0.170 (Papp, 1991, p. 20). The 1.04 Mt of scrap was estimated to have contained about 177,000 t of chromium valued at $882/t and to have had a primary-chromium-material-equivalent value of $157 million.

In 1998, reported receipts were 611,000 t of new and old stainless steel scrap, which were estimated to have contained 104,000 t of chromium. The difference between the chromium content of reported stainless steel scrap consumption and that of reported stainless steel scrap receipts was assumed to be equal to the chromium content of home scrap (73,000 t).

Chromium is used in alloy, carbon, stainless, and tool steels; cast irons; chemicals; and superalloys. Chromite is used in refractories. The amount of chromium added to carbon and alloy steel is small, and chromium is included in only a few grades. Many grades of these alloys do not have any added chromium. As a result, when recycled, these alloys are not sought for their chromium content. Stainless and tool steels and superalloys are more valuable, contain greater amounts of chromium, and contain chromium more universally than do carbon or alloy steels. These materials are sought for recycling because of their high value, their high content of desirable elements (such as nickel, cobalt, molybdenum, and chromium), and their lack of undesirable, or tramp, elements.

The carbon steel recycling rate is defined as carbon steel scrap consumption per carbon steel production on an annual basis. In the United States on average for 1994 through 1998, it exceeded the stainless steel recycling rate by about 15 percent. All grades of stainless steel contain chromium, whereas only a few grades of carbon steel contain chromium, and the quantities are small compared with those in stainless steel. Because of these circumstances, the amount of chromium contained in recycled carbon steel cannot be confidently estimated, and carbon steel recycling is not considered to contribute to chromium recycling in this study.

In the United States on average for 1994 through 1998, alloy steel was recycled at less than one-sixth the rate of stainless steel. The alloy steel recycling rate was measured by comparing the ratio of alloy steel scrap consumption to alloy steel production with the ratio of stainless steel scrap consumption to stainless steel production (AISI, 1995–99). The amount of alloy steel recycled was nearly 1 Mt in 1998. Only a few grades of alloy steel contain chromium, and the amounts are small compared with those in stainless steel. Because of these circumstances, the amount of chromium contained in recycled alloy steel cannot be confidently estimated, and alloy steel recycling is not considered to contribute to chromium recycling in this study.

Although the production of superalloys is small compared to that of stainless steel, their high value makes recycling superalloys cost effective. Nevertheless, data were not available to estimate the contribution of superalloy recycling to chromium recycling in this study.

DISSIPATED MATERIALS NOT AVAILABLE FOR RECYCLING

Dissipative uses do not result in new or old scrap generation in this model; they commonly involve dilution of the material or use in small volumes. Two broad categories of chromium products that are used dissipatively are chemicals and refractory materials; small amounts of chromium-containing steel can also be considered to be used dissipatively. For example, chromium is used in dyes and pigments that are subsequently incorporated in inks and paints. Because those inks and paints are used as thin coatings, the chromium becomes so diluted that recovery is uneconomic. Such materials leave the use cycle if incinerated or placed in a landfill.

For the purpose of estimating the amount of dissipative use, chemical and refractory material production would be a good start except that such information is company confidential and, therefore, is not available for this calculation. Because imported chromite ore was used to make chromium chemicals, chromite-containing refractory materials, and chromium ferroalloys, net chromite ore imports can be used to estimate dissipative use. Inclusion of net trade in chromium chemicals and stock change of chromite ore to refine that estimate indicates that U.S. dissipative chromium use in 1998 was 132,000 t.

Chromium ferroalloys are used to make the end-product iron and steel alloys discussed above. Some of that use is dissipative. The amount of chromite ore consumed in the United States in 1998 to make ferrochromium is the amount herein assumed to have been used dissipatively in metallurgical applications. Although there is no quantitative information about dissipative use, the assumption seems reasonable.

Because chromium ferroalloy and metal production data for 1998 were withheld, estimates made for 1997 are assumed to apply. Domestic ferrochromium production is estimated to have been reported domestic chromium ferroalloy and metal production less domestic chromium metal production. Chromium metal production in 1998 is estimated to have been 2,000 t, implying that 38,900 t of chromium contained in stainless steel was used dissipatively. That was 10.6 percent of chromium contained in the net stainless steel supply. The net stainless steel supply was material that entered the marketplace in products; it is calculated as stainless steel shipments plus net imports of stainless steel mill products. Applying this result to 1998 data indicates that 38,900 t of chromium contained in the 1998 net stainless steel supply was used dissipatively in metallurgical applications, or about 11.4 percent of chromium contained in stainless steel production. Because chromium not used dissipatively becomes old scrap supply, the above assumption further implies that 88.6 percent of the net stainless steel supply in 1998 will become old scrap.

OLD SCRAP GENERATED

Old scrap generated was estimated to be the net stainless steel supply of 30 years before 1998 adjusted for trade and dissipative use. Stainless steel is used in virtually all industry sectors. Stainless steel is stronger, more durable, and more valuable than common grades of steel. The actual lifetime of stainless steel parts depends on the specific applications, but data are lacking on the distribution of stainless steel by end use, average product life by end use, and recovered fraction by product; therefore, old scrap generated was estimated on the basis of the past domestic net stainless steel supply.

From 1994 through 1998, the United States was a net exporter of stainless steel. U.S. stainless steel ingot exports were in the range of 0.4 to 0.6 percent of domestic stainless steel production; semifinished stainless steel exports were 4 to 8 percent of that production. Stainless steel net exports in 1968 are assumed to have been balanced by stainless steel contained in net manufactured product imports. This leaves dissipative uses in 1968 to be accounted for. The same dissipative use pattern discussed above for 1997 is assumed to apply to 1968. Therefore, dissipative uses in 1968 were 10.6 percent of net stainless steel supply in 1968, leaving 89.4 percent of that supply potentially available for recycling. Thus, 89.4 percent of the 1968 net stainless steel supply is the input to old scrap generated in 1998.

Stainless steel production in 1968 contained about 221,000 t of chromium. The net stainless steel supply (that is, stainless steel shipments plus imports minus exports) contained 148,000 t of chromium, of which 89.4 percent became the estimated amount of old scrap generated in 1998, 132,000 t of chromium.

In mining terms, a "resource" is material available regardless of the economics of recovery, and a "reserve" is an economically recoverable resource—old scrap generated is a resource, and old scrap consumed is a reserve (U.S. Bureau of Mines and U.S. Geological Survey, 1980). This resource may or may not have been collected, sorted if collected, or traded if sorted. In effect, the scrap industry must undo what the wholesale and retail trade industries do—the wholesale and retail trade industries take goods concentrated at the point of production and distribute them to consumers, whereas the scrap industry takes distributed materials and concentrates them so that they can reenter the production process.

Various factors affect material collection and recycling (Aylen and Albertson, 1995). The availability of obsolete stainless steel scrap is price sensitive. In other words, when the price of scrap goes up, so does the supply of obsolete stainless steel scrap. The reason for this is that scrap collectors and processors stock obsolete stainless steel scrap until it becomes profitable for them to handle, process, and ship that material. On the basis of the resource/reserve analogy above, as price increases, resources become reserves.

Old superalloy scrap is generated when parts made of superalloy material, such as jet engine parts, are replaced. Chemicals, such as plating and metal finishing baths, are processed to extend their useful life by removing contaminants. To the extent that this processing is recycling, it produces home scrap because such renewal is done within a plant. Refractory materials, such as chromite casting sand, are processed for reuse. To the extent that this processing is recycling, it produces home scrap because such reuse is done within a plant.

Figure 2 shows the supply of chromium by material to the U.S. economy and the use of that material by end-use market sector. Figure 2*A* shows the distribution of chromite ore use by industry from 1978 to 1994; data are given individually for the chemical, metallurgical, and refractory industries from 1978 through 1985, but data are combined for the chemical and metallurgical industries from 1986 through 1994 to protect company proprietary data. After 1994, publication of chromite ore consumption by industry was discontinued to protect proprietary data.

As shown in figure 2*A*, from 1978 through 1985, consumption of chromium from chromite ore by the chemical industry declined by 7 percent; consumption by the metallurgical industry dropped by half, to 65,200 t from 132,000 t; and consumption by the refractory industry dropped more than two-thirds, to 15,400 t from more than 53,800 t. Refractory industry consumption continued to drop until it reached less than 6,000 t in 1994, when reporting was discontinued. From 1979, a peak consumption year, to 1994, the chromium contained in the reported annual chromite ore consumption dropped to just more than 100,000 t from about 300,000 t. Chromite ore was being replaced by ferrochromium as the major source of chromium for the U.S. economy. Ferrochromium is used in the metallurgical industry, which is the major source and consumer of chromium-bearing scrap.

Figure 2*B* shows the relative importance of the two major commercial sources of chromium in the United States during the 20 years, 1978–98. The figure shows that the dominant source of chromium for the U.S. economy shifted from chromite ore before 1981 to ferrochromium after 1983; for example, chromite ore supplied 61 percent of chromium contained in these imports in 1978, whereas ferrochromium supplied more than 67 percent of chromium in 1998.

The major end use of chromium in the metallurgical industry is the manufacture of stainless steel. Figure 2*C* shows the inferred distribution of chromium among major end-use market sectors, which are electrical and electronic equipment, fabricated metal products, industrial and commercial machinery, and transportation. Transportation and industrial and commercial machinery each accounted for more than 40 percent of the total; fabricated metal products and electrical and electronic equipment each accounted for under 10 percent.

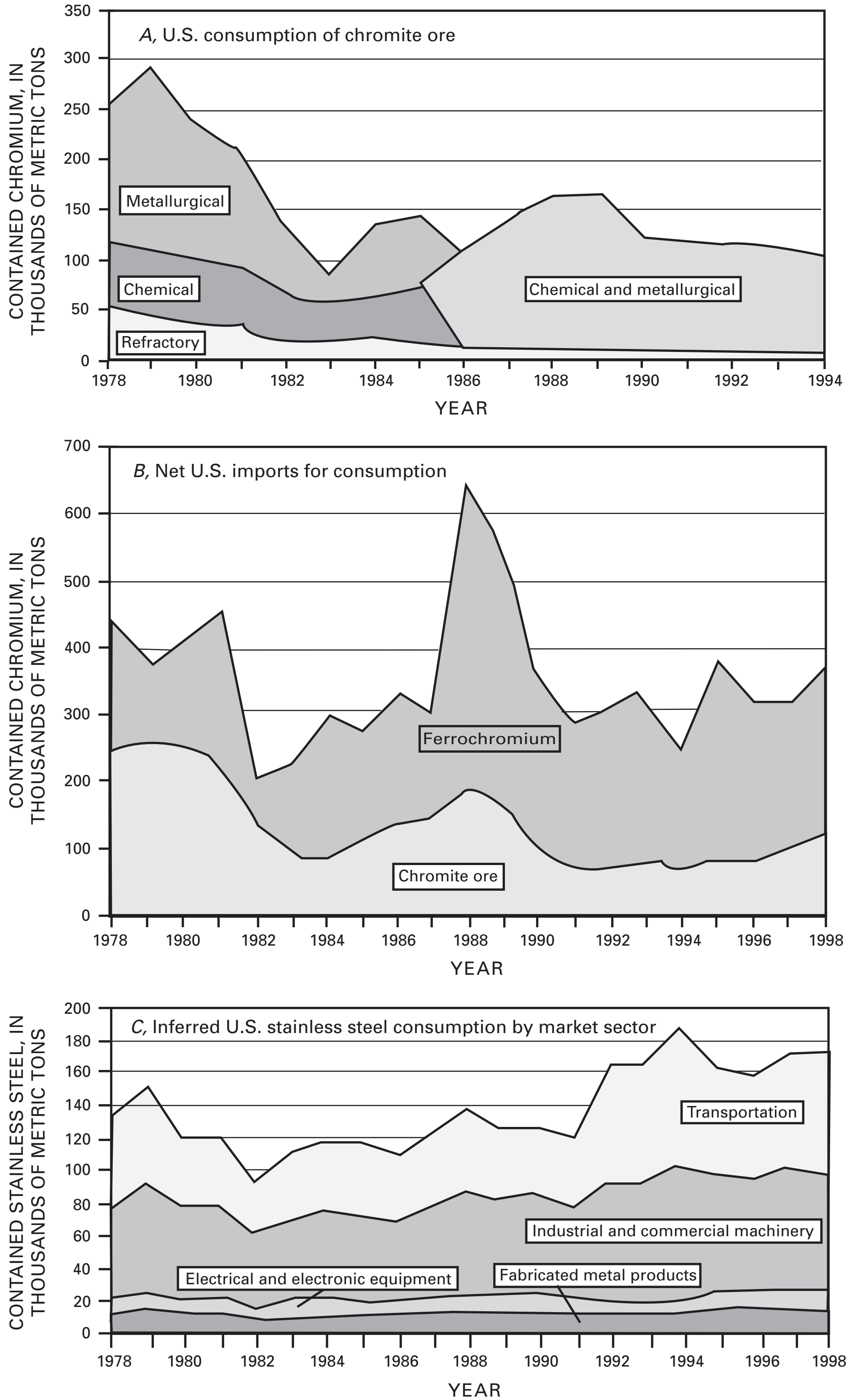

Figure 2. U.S. chromium source materials and consumption from 1978 through 1998. *A,* Reported U.S. consumption of chromite ore by the metallurgical, chemical, and refractory industries (data through 1994 only). *B,* Net U.S. imports for consumption by material. *C,* Inferred U.S. stainless steel consumption by market sector.

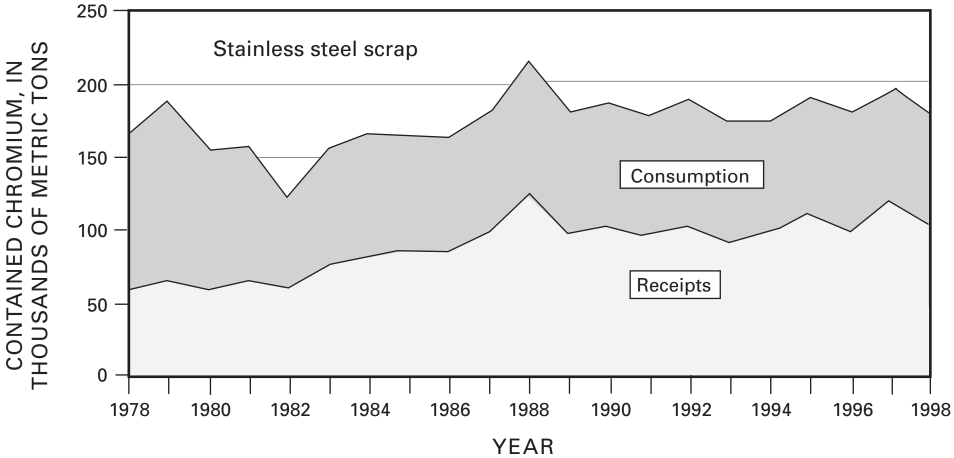

Figure 3. U.S. chromium recycling trend as indicated by reported consumption and receipts of stainless steel scrap from 1978 through 1998.

Figure 3 shows reported consumption and receipts of stainless steel scrap from 1978 through 1998. Assuming that scrap receipts are new or old scrap, one may infer that scrap receipts shown in figure 3 came from the end-use manufacturing processes shown in figure 2*C* or from the products of those uses. If the difference between scrap receipts and scrap consumption in figure 3 is home scrap, then the source of that scrap is the primary metals industry market sector. The figure shows a trend of increasing importance of new and old scrap, as shown by the increasing amount of scrap receipts compared with scrap consumption, during the 20-year period. Scrap receipts accounted for less than 36.8 percent of consumption in 1978 compared with 58.7 percent in 1998.

NEW SCRAP

New scrap results from steel fabrication processes. Stainless steel is either wrought or cast to make shapes, such as bars, plates, sheets, or strips, that are used to manufacture products. New scrap is valuable and is returned to the stainless steel producer through the supplier-purchaser channel or through scrap processors and dealers.

New stainless steel scrap generation is proportional to stainless steel use. Reducing the amount of new scrap generated per unit of stainless steel production increases processing efficiency. The constancy of new scrap availability in the face of continued average production growth indicates that processing efficiency has increased coincident with and proportional to the growth in production. New scrap availability is not as price sensitive as old scrap availability because it is easier to collect, sort, and return new scrap; commonly, new scrap is returned under formal contract arrangements (Friedrich Terörde, ELG Haniel Group, U.S.A., 1997, written commun.). New scrap may also be called prompt industrial scrap because it is generated when industry manufactures products that use stainless steel and is returned as it is generated; that is, promptly.

Stainless steel production has been growing; from 1950 to 1996, the compounded annual growth for the major producing countries was 6.0 percent (INCO Limited, 1997, p. 6). Annual growth of stainless steel production for these countries from 1986 through 1996 ranged in magnitude from as little as 0.04 percent to more than 14 percent.

For the secondary material flow model used in this report, new scrap generated was estimated on the basis of information from Austin van't Wout (Capricorn BV, Holland, 1998, written commun.) that 25 to 30 percent of scrap shipped by scrap suppliers to the stainless steel industry is new scrap. Thus, because scrap receipts were 58.7 percent of scrap consumption in 1998 and new scrap was 25 to 30 percent of scrap receipts (receipts by stainless steel producers being the same as shipments from scrap processors), new scrap was 14.7 to 17.6 percent of stainless steel scrap consumption, and the new-to-old-scrap ratio was 28:72.

In written communications in 1997, P.J. Probert (Hernic Ferrochrome, South Africa) and Josephine Ward (Reward Raw Materials, Inc., Carnegie, Pa., U.S.A.) discussed secondary chromium consumption. Probert reported that stainless steel scrap typically provided 35 to 40 percent of the chromium required to produce stainless steel worldwide. For austenitic grades (those requiring nickel), scrap provided 45 to 50 percent of the required chromium units. Ward estimated the lifetime of stainless steel products to range from 15 to 20 years in the United States and stainless steel scrap to comprise 50 percent reclaimed (old scrap), 35 percent revert (home scrap), and 15 percent industrial (new scrap) in the United States. This estimate suggests that 65 percent of scrap consumption is receipts. U.S. stainless steel receipts and consumption reported to the U.S. Geological Survey (USGS) indicate that receipts averaged 59 percent of stainless steel scrap consumption during 1994 through 1998. The new scrap percentage of net stainless steel scrap consumption inferred in this report from other sources is 16.2 percent.

In a study of nickel that is more recent than the studies cited in the previous paragraph, Salamon (2000) reported the lifetime of stainless steel in buildings to be 70 years; industrial plants, 35 years; and consumer products, 5 to 25 years.

Chemicals do not contribute to new scrap.

DISPOSITION OF CHROMIUM-CONTAINING SCRAP

Scrap processors collect old and new scrap, segregate it by grade, and cut it to usable size. They commonly mix scrap to meet the chemical specifications of the stainless scrap consumers who use it as a feed material for their furnaces. The USGS monitors scrap consumption of the U.S. stainless steel industry. The industry reports scrap receipts and scrap consumption. Stainless steel scrap accounting procedures do not differentiate old from new scrap.

In the model presented here, the difference between old scrap supply and old scrap consumed is taken as the sum of old scrap exported, old scrap going into stocks, and unrecovered old scrap. The rate of recovery of old scrap from the general economy by scrap dealers and processors is unknown. Old scrap generated is an estimated number. Old scrap consumed is estimated to be the difference between scrap receipts (a surveyed quantity) and new scrap consumed (an estimated quantity). Unrecovered old scrap is estimated by balancing old scrap supply inputs and outputs.

In 1998, 1.04 Mt of stainless steel scrap was consumed to produce 2.01 Mt of stainless steel. In other words, the stainless steel industry consumed the equivalent of 51.8 percent of production in stainless steel scrap, an amount similar to the overall steel industry recycling performance of 58.4 percent, which is based on American Iron and Steel Institute (AISI) data averaged from 1994 through 1998 (AISI, 1999).

Individual stainless steel producers reported scrap usage ranging from 0 to 80 percent. One company reported feed consisting of 20 percent in-house (home) scrap, 30 percent primary (previously unused) materials, and 50 percent secondary materials (new plus old scrap). By using reported stainless steel scrap receipts and consumption, secondary supply could be estimated as receipts, and in-house scrap could be estimated as consumption minus receipts; by using production to estimate feed, primary supply could be estimated as production minus scrap consumption. For the U.S. stainless steel industry, this process averaged from 1994 through 1998 yields the following stainless steel scrap types as percentages of stainless steel production: 22.2 percent in-house scrap; 46.1 percent primary materials, and 31.7 percent secondary materials.

The U.S. Environmental Protection Agency (EPA) reported the release and transfer of from 12,000 t to 42,000 t of chromium annually between 1987 and 1995 from the primary metals industry, which for chromium is the steel industry (Papp, 1994, p. 72; 1996; 1997, p. 182; 1998, p. 196). In 1991, industry started reporting recycling as part of transfers (EPA, 1993, p. 6, 144, 162). As a result, transfers increased from about one-half of releases plus transfers to about three-fourths. One could conclude that in excess of one-half of the reported 40,000 t of transfers in 1991 were recycled. In the model used here, this material would be classified as either home or new (prompt) scrap.

The above discussion of scrap disposition focuses on stainless steel scrap because it is accounted for separately from carbon steel, alloy steel, and superalloys. The chromium in stainless steel can reasonably be estimated, whereas the chromium in the other materials cannot, although brief discussions are provided above in the section, “Sources of Chromium-Containing Scrap.”

OLD SCRAP RECYCLING EFFICIENCY

Old scrap recycling efficiency is defined as old scrap consumed plus old scrap exported as a percentage of old scrap generated plus old scrap imported plus old scrap stock released; it shows the relations among what is theoretically available for recycling, what is recovered, and what is not recovered. For U.S. chromium in 1998, old scrap recycling efficiency was 87 percent. As mentioned above in the section on “Old Scrap Generated,” the availability of old stainless steel scrap is price sensitive. Therefore, the resource of old scrap is closely monitored and converted to commercial product when it is economically possible to do so. In an economic sense, old stainless steel scrap is being fully used consistent with the economic constraints placed upon its recycling by our economy.

INFRASTRUCTURE OF CHROMIUM-CONTAINING SCRAP

Scrap collection takes different forms on the basis of the kind and quantity of scrap. For example, scrap generated in the manufacturing process (new scrap) has value because its composition, quality, and origin are known. One recycling expense is the cost of separating materials into usable groups. Manufacturers can avoid this cost by not mixing incompatible materials, then returning the material to the metal producer for reuse. Recycling obsolete products is more labor intensive than recycling new scrap because the products are a mixture of materials that need to be segregated. For some products, high-value materials are efficiently segregated from low-value ones. For example, automobile catalytic converters are housed in stainless steel cans. Because many automobiles are recycled, the cans are economically reclaimed and their material is reused.

Although not all stainless steel in household products is recovered, much of the stainless steel in industrial products is. The stainless steel scrap industry includes suppliers of scrap to stainless steel producers and collectors of scrap who also sort material. Functions performed by these two groups—collecting, sorting, storing, and distributing—overlap. The scrap supplier takes on the responsibility for meeting the quality requirements of stainless steel producers. Scrap collectors are among their sources of scrap (Austin van't Wout, 1998, written commun.).

The U.S. Harmonized Tariff System categorizes chromium metal import trade into waste and scrap and other; "other" includes wrought and unwrought chromium alloys. The system makes no such breakdown for chromium metal exports. Vastly more chromium is traded as part of stainless steel than is traded in chromium waste and scrap. In 1998, U.S. exports of chromium metal (including waste and scrap) were 1,038 t; in contrast, stainless steel scrap net exports (net exports are old scrap exported minus old scrap imported) of 241,000 t, gross weight, contained an estimated 41,000 t of chromium. Chromium contained in stainless steel scrap net exports was 23 percent of chromium contained in domestic stainless steel scrap consumption. Only stainless steel scrap is included in this report because it dominates the quantity of chromium recycled and because it is the material for which information is available.

PROCESSING OF SCRAP METALS

SMELTING/REFINING

In the steel industry, smelting is the process of converting iron ore into iron. Chromium plays no role in this process. In the chromium industry, smelting is the process of converting chromite ore into ferrochromium. Steelmaking, in particular stainless steelmaking, is a refining process that involves combining iron and alloying elements to convert iron into steel. Steel is iron with carbon added. Chromium is one of the alloying elements added to iron to make stainless steel. The source of chromium could be ferrochromium or stainless steel scrap. Ferrochromium is the primary supply because it comes directly from mined materials, and stainless steel scrap is the secondary material because it is recycled material. Stainless steel scrap is mixed with ferrochromium and other feed materials, melted, and refined. Because primary and secondary materials are processed together in the stainless steelmaking process, secondary material metallurgical processing losses are the same as those of primary material.

FABRICATION

Scrap generated in the fabrication industry may require processing before it is reusable. For example, only certain sized objects are permissible for materials handling and furnace feed. Large objects must be cut; small ones, agglomerated. Contaminants must be removed. Cutting operations require lubricants that may have to be cleaned off of the metal before it is reused.

OUTLOOK AND SUMMARY

Chromium is recycled as part of stainless steel recycling. Once it is reclaimed, stainless steel scrap is processed and sold to be used as a feed material in the stainless steel production process. The scrap is mixed with other feed materials, including primary materials, and is melted and refined.

The U.S. stainless steel industry in 1998 produced stainless steel scrap in excess of its needs. With a chromium recycling rate of 20 percent and old scrap recycling efficiency of 87 percent as interpreted in this model, chromium recovery from obsolete material might be improved. Figures indicate that in 1998, 18,000 t of chromium could theoretically have been obtained from unrecovered old scrap. Although furnaces in industrialized countries (probably including the United States) produced stainless steel using as much as 80 percent scrap, the U.S. market did not absorb this additional material under 1997–98 conditions of relatively strong demand. Price, of course, is a major inducement, and prices were relatively low in 1998. The 18,000 t is an estimate that could be off for several reasons—dissipative use could have been underestimated, old scrap supply could have been overestimated, or high-cost stocks may have built up in scrap yards.

New scrap recycling efficiency is high relative to that of old scrap and likely cannot be improved significantly. Recycling of stainless steel in a wide variety of products, however, is the area where attention could be focused. Some believe that greater design for recycling would aid in this effort for a more sustainable environment. In 1998, the United States had net exports of stainless steel scrap containing 41,000 t of chromium that earned the United States $154 million. The U.S. stainless steel industry reported consuming 1.04 Mt of home, new, and old stainless steel scrap that was estimated to have contained about 177,000 t of chromium and to have had a primary-chromium-material-equivalent value of $157 million.

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APPENDIX—DEFINITIONS

apparent consumption. Primary domestic production plus secondary domestic production (old scrap) plus imports minus exports plus adjustments for Government and industry stock changes. For chromium, there is insufficient information about recycling to distinguish between new and old scrap consumption. Chromium apparent consumption is approximated by chromium apparent supply (see definition below) where new plus old scrap production is defined as stainless steel scrap receipts as reported in the U.S. Geological Survey's Iron and Steel Scrap Survey (Fenton, 2000, and updates by Duane Johnson, 2000, unpub. data).

apparent supply. Apparent consumption calculated with secondary production equal to new plus old scrap; see *apparent consumption.*

dissipative use. A use in which a metal is dispersed or scattered, such as paints or fertilizer, making it exceptionally difficult and costly to recover the metal.

home scrap. Scrap generated as process scrap and consumed in the same plant where generated.

new scrap. Scrap produced during the manufacture of metals and articles for both intermediate and ultimate consumption, including all defective finished or semifinished articles that must be reworked. Examples of new scrap are borings, castings, clippings, drosses, skims, and turnings. New scrap includes scrap generated at facilities that consume old scrap. Included as new scrap is prompt industrial scrap—scrap obtained from a facility separate from the recycling refiner, smelter, or processor. Excluded from new scrap is home scrap that is generated as process scrap and used in the same plant.

new-to-old-scrap ratio. New scrap consumption compared with old scrap consumption, measured in weight and expressed in percent of new plus old scrap consumed (for example, 40:60).

old scrap. Scrap including (but not limited to) metal articles that have been discarded after serving a useful purpose. Typical examples of old scrap are electrical wiring, lead-acid batteries, silver from photographic materials, metals from shredded cars and appliances, used aluminum beverage cans, spent catalysts, and tool bits. This is also referred to as post-consumer scrap and may originate from industry or the general public. Expended or obsolete materials used dissipatively, such as paints and fertilizer, are not included.

old scrap generated. Metal content of products theoretically becoming obsolete in the United States in the year of consideration, excluding dissipative uses.

old scrap recycling efficiency. Amount of old scrap recovered and reused relative to the amount available to be recovered and reused. Defined as (consumption of old scrap (COS) plus exports of old scrap (OSE)) divided by (old scrap generated (OSG) plus imports of old scrap (OSI) plus a decrease in old scrap stocks (OSS) or minus an increase in old scrap stocks), measured in weight and expressed as a percentage:

$$\frac{\mathrm{COS} + \mathrm{OSE}}{\mathrm{OSG} + \mathrm{OSI} + \text{decrease in OSS or} - \text{increase in OSS}} \times 100$$

old scrap supply. Old scrap generated plus old scrap imported plus old scrap stock decrease.

old scrap unrecovered. Old scrap supply minus old scrap consumed minus old scrap exported minus old scrap stock increase.

primary production. Chromium from ore. Because chromite ore was not mined in the United States in 1998, the primary domestic production term used in calculating apparent consumption is zero.

recycling. Reclamation of a metal in usable form from scrap or waste. This includes recovery as the refined metal or as alloys, mixtures, or compounds that are useful. Examples of reclamation are recovery of alloying metals (or other base metals) in steel, recovery of antimony in battery lead, recovery of copper in copper sulfate, and even the recovery of a metal where it is not desired but can be tolerated—such as tin from tinplate scrap that is incorporated in small quantities (and accepted) in some steels, only because the cost of removing it from tinplate scrap is too high and (or) tin stripping plants are too few. In all cases, what is consumed is the recoverable metal content of scrap.

recycling rate. Fraction of the metal apparent supply that is scrap on an annual basis. It is defined as (consumption of old scrap (COS) plus consumption of new scrap (CNS)) divided by apparent supply (AS), measured in weight and expressed as a percentage:

$$\frac{\mathrm{COS} + \mathrm{CNS}}{\mathrm{AS}} \times 100$$

secondary production. Chromium from recycling of new plus old scrap.

superalloys. Alloys developed for high-temperature conditions where stresses (tensile, thermal, vibratory, and shock) are relatively high and where resistance to oxidation is required.

value. Unit value of primary metal applied to primary metal contained in scrap. For chromium, the primary metal is ferrochromium.